A SEARCH FOR SOLAR FLARE POSITRONS

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The detection of solar γ-ray line emission and observations of the isotopes ^2H, ^3H and ^3He in solar cosmic rays provide direct evidence for the occurrence of high energy nuclear reactions in solar flare events. Appreciable numbers of other reaction products, including positrons with energies near ~ 1 MeV, should also be produced in such events. We have searched for positrons in the 0.16-1.6 MeV energy interval during 5 "^3He rich" solar particle events observed by the Caltech Electron/Isotope Spectrometers on IMP 7 and 8. Based on calculations of positron and ^3He production at the sun, and using a simplified model of interplanetary propagation, we might expect comparable fluences of positrons and ^3He to be observed. Summing over these 5 events, however, we find the 0.16 to 1.6 MeV positron fluence to be $\leqslant$ 10% of the > 1 MeV/nuc ^3He fluence. This suggests that other processes, such as preferential trapping by the solar magnetic field, may be important.

1. Introduction. Chupp et al. (1973) have reported the identification of a line flux of 0.5 MeV γ-radiation during the large solar particle events of August 1972. These observations imply the existence of appreciable numbers of solar positrons during periods of intense solar activity, presumably the products of nuclear interactions of flare accelerated particles with the ambient solar atmosphere. Additional evidence for nuclear reactions on the sun has been provided by the identification of the rare isotopes ^2H, ^3H, and ^3He in solar cosmic rays, including a number of events that had anomalously large relative abundances of ^3He without corresponding enhancement in ^2H or ^3H (Garrard et al., 1973; Anglin et al., 1974; Serlemitsos and Balasubrahmanyan, 1974; Hurford et al., 1975a). In these unusual events, labeled "^3He rich flares", the $^3He/^4He$ ratio ranges from ~ 0.2 to $\geqslant$ 6, while the $^3He/^1H$ ratio can be as large as ~ 1.

Models that attempt to explain this unusual isotopic composition have been proposed by Ramaty and Koslovsky (R & K) (1974a, 1974b) and Rothwell (1974). Appreciable production of other nuclear reaction products, including nuclear γ-rays, neutrons, and positrons is also predicted in such models (Ramaty and Lingenfelter, 1973; Ramaty et al., 1975; Wang and Ramaty, 1975). A principal source of positrons is the β^+-decay of short-lived nuclear reaction products such as ^{11}C, ^{13}N, and ^{15}O. The β^+-decay energies of these nuclei are within the 0.16-1.6 MeV energy range covered by this experiment. Simultaneous observation of solar flare positrons and rare isotopes of secondary origin would provide important information for studying solar flare regions, acceleration processes, and particle propagation.

In this paper we report upper limits to the fluence of ~ 1 MeV solar flare positrons in 5 ^3He rich solar particle events, and compare these results with calculated fluxes of solar flare positrons.

2. The Instruments. The observations reported here were made with the Caltech Electron/Isotope Spectrometers (EIS) on IMP-7 (launched September 1972) and IMP-8

(launched October 1973). The IMP-7 detector system, shown in *Figure 1*, consists of a stack of eleven silicon surface-barrier detectors, D0 through D10, surrounded by a plastic-scintillator anticoincidence cup D11. Detectors D0, D1, D3, and D4 are annular devices. All silicon detectors except D2 have nominal thicknesses of 1 mm and thresholds of ~ 160 keV, and are thus fully sensitive to penetrating minimum-ionizing particles.

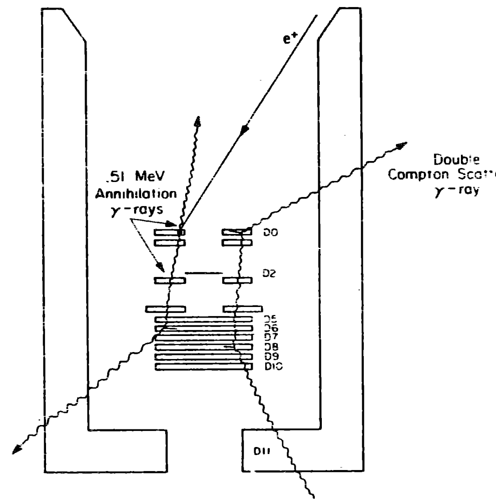

Fig. 1. Cross section of the Caltech IMP-7 EIS illustrating one mode of positron detection and a possible background event due to a double-Compton-scattered γ-ray.

The EIS instruments have two modes of charged particle detection relevant to the present discussion. In the narrow geometry mode, the annular detectors serve as an active collimator, and we analyze events in detectors D2, and D5 through D9. The 50 μm detector, D2, allows clean electron-nuclei separation. The isotopes of nuclei that trigger D2 and D5 can be identified using conventional dE/dx-E techniques. For ^{1}H and ^{4}He nuclei the D2D5 energy range is 2.4-12.7 MeV/nuc, while for ^{3}He it is 2.9-15 MeV/nuc. In the Wide Geometry Mode, we analyze events which trigger D0 without penetrating to D10 or D11. A more complete discussion of the IMP-7 EIS can be found in Hurford et al. (1974), while the IMP-8 EIS is of similar design and operation with somewhat improved positron detection sensitivity.

Positrons are identified by detecting their annihilation γ-radiation, as illustrated in *Figure 1*. If an incident positron stops in D0, one of the 0.51 MeV annihilation γ-rays may Compton scatter in another detector such as D6, D7, D8, or D9. Thus the coincidences D0D6, D0D7, D0D8, or D0D9, in anticoincidence with all other detectors, would be positron signatures. Pulse height information can then be used to assign an energy to the particle stopping in D0, and to ensure that the energy loss in the 2nd detector is consistent with the maximum Compton recoil energy of a 0.51 MeV γ-ray.

The instruments' efficiency for identifying positrons has been established by calibration and calculation. For positrons stopping in D0 it is ~ 3 x 10^{-3} for the IMP-7 EIS, and ~ 9 x 10^{-3} for the IMP-8 EIS. The principal background source of events with positron like signatures is γ-rays which Compton scatter in two separate detectors, a possible example of which is illustrated in *Figure 1*.

During solar quiet times we measure a very constant rate of positron-type events, a significant fraction of which is known to be due to double-Compton-scattered γ-rays (Hurford et al., 1973). A significantly enhanced flux of positrons during a solar flare would result in a temporary increase in the rate of positron-type events above this quiet time level.

3. Solar Flare Observations. We have searched for solar flare positrons during five ^{3}He rich solar flares identified by the IMP-7 EIS (see e.g. Hurford, 1974, Hurford et al., 1975a, b). In these events, summarized in Table 1, the 2.9-15 MeV/nuc $^3He/^4He$ ratio ranged from ~ 0.2 to $\geqslant$ 6 while the observed ^{3}He fluences were all comparable. Note that the last two events occurred after the launch of IMP-8, permitting significantly improved positron detection sensitivity. An analysis of daily event rates for 20 day periods centered on each of these five flares showed no statistically significant ($\geq 3\sigma$) increases in the rate of positron-like events. *Figure 2* shows a superposition of data from two ^{3}He rich events observed by IMP-8, and the five ^{3}He rich events observed by IMP-7, centered on the days during which ^{3}He nuclei were first detected at 1 AU. Note that the average counting rates of positron-like events near the time of the ^{3}He rich flares do not differ significantly from the mean counting rates averaged over longer time periods.

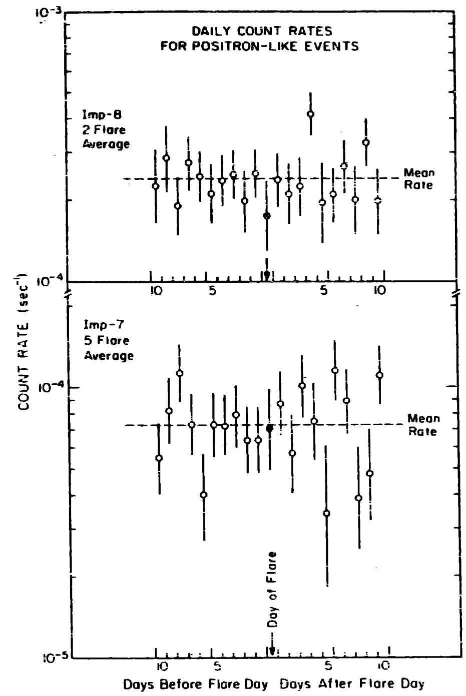

Fig. 2. Counting rates of positron-like events at the time of ^{3}He rich flares. Statistical uncertainties of ± 1 σ are indicated.

TABLE 1. SOLAR PARTICLE FLUENCES

YEAR	START		END		INSTRUMENT	POSITRONS 0.16-1.6 MeV ($cm^{-2}sr^{-1}$)	TOTAL ELECTRONS 0.16-16 MeV ($cm^{-2}sr^{-1}$)	^{3}He 2.9-15 MeV/nuc ($cm^{-2}sr^{-1}$)
1973	2/14	2000	2/15	0000	IMP-7	$< 2 \times 10^3$	$\sim 10^5$	$\sim 3 \times 10^2$
1973	6/29	0000	6/29	1500	IMP-7	$< 10^3$	$\sim 10^5$	$\sim 3 \times 10^2$
1973	9/5	0300	9/6	0000	IMP-7	$< 2 \times 10^3$	$\leqslant 10^4$	$\sim 3 \times 10^2$
1974	2/20	1200	2/22	0000	IMP-7,8	$< 1.2 \times 10^3$	$\sim 3 \times 10^5$	$\sim 6 \times 10^2$
1974	5/9	0800	5/10	0000	IMP-7,8	$< 4 \times 10^2$	$\leqslant 2 \times 10^4$	$\sim 6 \times 10^2$
	IMP-7	5-FLARE SUM			IMP-7	$< 5 \times 10^3$	$\sim 5 \times 10^5$	$\sim 2 \times 10^3$
	IMP-7,8	2-FLARE SUM			IMP-7,8	$< 1.0 \times 10^3$	$\sim 3 \times 10^5$	$\sim 1.2 \times 10^3$

In order to obtain upper limits to the solar positron fluence, data from more restricted time intervals were analyzed, starting ~ 2 to 4 hours before the particle onset at 1 AU, and extending to include at least 90% of the flare associated ^{3}He and total electron fluences observed. The results of this analysis are summarized in Table 1, where the upper limits to the solar positron fluence represent the 84% confidence limits after subtracting the quiescent event rates shown in *Figure* 2. Also shown are the ^{3}He and total electron fluences that we observe.

4. Discussion. The results in Table 1 indicate that positrons comprise $\leqslant$ 1% of the total electrons near 1 MeV in ^{3}He flares, a result similar to that found for flares of normal isotopic composition (Hurford et al., 1973). Note, however, that it is more meaningful to compare the positron and ^{3}He fluences, since both these species are believed to be of secondary origin. For this purpose it is useful to obtain a better estimate of the total ^{3}He fluences, including particles with energies less than our D2D5 coincidence threshold of 2.9 MeV/nuc. For the two ^{3}He rich events observed by IMP-8, Gloeckler and Hovestadt (1975) have determined that the ^{3}He spectrum extends down to $\leqslant$ 1 MeV/nuc. Assuming $dj/dE \propto E^{-3}$ in this and later estimates (Hurford, 1974), we estimate a total ^{3}He fluence > 1 MeV/nuc of ~ $10^4 cm^{-2} sr^{-1}$ for the 20 Feb. and 9 May 1974 flare sum, giving a ratio of positron to ^{3}He fluences of < 0.1. Note that this is a conservative estimate since there is no evidence to suggest that the ^{3}He spectrum cuts off at 1 MeV/nuc.

In order to estimate the relative abundances of positrons and ^{3}He produced in nuclear reactions at the sun, we consider the thick target model of R & K (1974a, b) which is designed to explain the observed enhancement of ^{3}He relative to other secondary nuclei such as ^{2}H and ^{3}H. In this model a primary beam of ^{1}H, ^{4}He and CNO nuclei is directed downwards on the ambient solar atmosphere of similar composition. Based on reaction kinematics calculations, R & K find that for products produced in the backward hemisphere of the laboratory reference frame, which includes ~ 30% of the total ^{3}He, it is possible to obtain $^3He/^2H \geqslant 30$ at energies $\leqslant$ 1 MeV/nuc. A post-production acceleration process is then required for the ^{3}He nuclei to escape from the sun.

From the calculations of R & K (1974a, b) and Ramaty et al. (1975) for this model, we estimate a total yield of ~ 0.1 positron emitters per ^{3}He produced, where we assumed that the primary beam directed into the sun had a spectrum $dJ/dP \propto \exp(-P/P_0)$, with characteristic rigidity P_0 = 150 MV. About 1/3 of the positron emitters will be β^+ unstable CNO nuclei yielding positrons in our energy range (~ 1 MeV). Assuming isotropic β^+-decay emission, we estimate a positron to ^{3}He ratio of ~ 0.05 in the backward lab hemisphere, and assume for convenience that this ratio is preserved in the particle fluxes escaping from the sun.

The relative β^+ and ^{3}He fluences observed at earth will depend on the nature of their propagation in the interplanetary medium. If scattering in the interplanetary magnetic field is sufficient to produce approximately isotropic particle fluxes, and if the e^+ and ^{3}He residence times near 1 AU are comparable, then we might expect the e^+ and ^{3}He number densities (cm^{-3}) to reflect their production ratio, i.e., $N(e^+) \simeq 0.05\, N(He^3)$. In this case the greater velocity of the positrons implies a fluence ratio of $F(e^+)/F(He^3) \sim 1$. If, in the other extreme, the e^+ and ^3He propagation is scatter free, we expect $F(e^+)/F(He^3) \sim 0.05$. These estimated fluence ratios should be compared to the observed upper limit of $F(e^+)/F(He^3) < 10^{-1}$, which is obtained by considering the ^3He fluence down to 1 MeV/nuc. The actual ratio could, of course, be up to a factor of ~ 100 lower if the ^3He spectrum extends down to 0.1 MeV/nuc with the same slope.

The above considerations imply that ~ 1 MeV positrons may not be released into the interplanetary medium as efficiently as ^3He nuclei, suggesting that processes other than those discussed may be important. Since in the thick target model of R & K, both the positrons and ^3He are produced at depths in the solar atmosphere of ~ 1-10 g/cm^2, it is clear that some post-acceleration process is required (R & K, 1974a, b) for either the e^+ or ^3He to escape the sun. Such an acceleration process might favor ^3He relative to positrons, or might accelerate the positrons to energies $\geqslant$ 2 MeV. Preferential trapping of positrons by the solar magnetic field might also be important. If, in fact, the majority of positrons do annihilate at the sun, the resulting 0.51 MeV γ-radiation might be observable at 1 AU, although estimates of the γ-ray flux from ^3He rich events (R & K, 1974a) are not so large as in the events observed by Chupp et al. (1973).

The uncertainties involved in the direct escape of ~ 1 MeV positrons from the sun can be avoided if we consider only those positrons that result from the β-decay of flare accelerated nuclei which escape into the interplanetary medium before decaying. R & K (1974b) suggest that boron should also be enriched in ^3He rich events, with a B/C ratio comparable to the $^3He/^4He$ ratio, although observations to date have not tested this prediction. A principal source of boron production in the thick target model of R & K is reactions that produce ^{11}C, such as $^{14}N(p, \alpha)^{11}C \rightarrow {}^{11}B + e^+ + \nu$. Note that ^{11}C also happens to be the principal source of ~ 1 MeV positrons in their model. Since the ^{11}C half-life is 20.5 min, the ^{11}C may be well into interplanetary space before it decays. Assuming that other β-unstable secondary products will be enriched to the same extent in these events, we find from R & K (1974a) and R & L (1973) that the ratio of flare accelerated β^+ emitters to ^3He should be ~ 10^{-2}, implying an interplanetary $e^+/^3He$ ratio of this same magnitude, once these nuclei have decayed. For the two simple propagation models considered above, the positron to ^3He fluence ratio will range from ~ 10^{-2} to ~ 0.2. Notice that this more realistic estimate of the positron and ^3He fluences, while not inconsistent with our observations, is well within the range of our measurement capabilities. We conclude that further comparison of observation and theory may prove fruitful for understanding high energy nuclear reaction processes which are associated with solar flares.

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6. References.

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